Edmonton, November 1990

Re. File No. 014SQ.23440-8-9067-01-SQ
CANMET Contract with Berkowitz Consulting Inc.

CARBON MONOXIDE AS INDICATOR FOR EARLY DETECTION OF SPONTANEOUS HEATING IN STORED COAL

AN EXPLORATORY STUDY

FINAL REPORT

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37 pp

MICROMEDIA

EXECUTIVE SUMMARY

While the mechanisms of 'spontaneous combustion' of coal - more properly referred to as autogenous heating - are now fairly well understood, and hazards from it can be minimized by following some empirical rules for coal stockpiling, there exist currently no means for reliably locating and monitoring developing 'hot spots' within coal piles. This study explored a procedure that could prove practical for that purpose. Based on the fact that atmospheric oxidation of coal generates carbon monoxide, it proposes to measure CO concentrations at specified locations in a pile and to use these data for construction of CO concentration surfaces which, by their departure from planarity, indicate hot spot sites.

This concept was evaluated in the laboratory by using a 45 cm cubic reactor into which gas could be injected through a series of ports and gas samples withdrawn from porous monitor tubes which traversed the reactor. Experiments centered on simulated coal oxidation as well as on O_2-sustained oxidation of coal at elevated temperatures.

For simulation experiments, the reactor was packed with polystyrene 'peanuts'; a hot spot was created by injecting CO near the bottom of the reactor; and air flow through a stockpile, which would cause CO spreading, was simulated by introducing a slow stream of nitrogen close to the CO injection port. Gas samples for analysis were collected from three locations in each monitor tube, and measured CO concentrations were then used to construct CO concentration surfaces at various levels in the reactor.

For coal oxidation runs, the reactor was loosely packed with crushed (+28 mesh) coal; a small electric heater was inserted immediately below the coal element in which a 'hot spot' was to be created; the coal temperature was raised to c.220°C; and sufficient oxygen was injected near the base of the developing hot spot to sustain oxidation of the coal. As before, gas samples were collected from variously sited monitor tubes, and analytical data were used for construction of CO concentration surfaces.

In all instances, except where effectively precluded by the scale of experimentation, these surfaces located the hot spot quite accurately. The exceptions were cases in which the 'areas of influence' of two hot spots overlapped, or where CO streams from hot spots on opposite sides of the reactor 'collided'. A test that examined possible use of CO_2 - which coal oxidation generates concurrently with CO - as an alternative gas for monitoring hot spots also furnished data that precluded accurate siting of hot spots and was therefore not further pursued.

The information accruing from this study makes it worthwhile to continue experimentation with a larger coal stockpile in order to develop the procedure further.

SOMMAIRE EXECUTIF

Alors que les mécanismes de 'combustion spontanée' du charbon - plus proprement appelée chauffage autogène - sont désormais assez bien compris, et que les risques qui en découlent peuvent être minimisés en suivant des règles empiriques pour l'empilement du charbon, il n'existe à présent aucun moyen pour localiser d'une manière sûre et suivre les 'points chauds' qui se développent dans les piles de charbon. Cette étude a exploré une procédure qui purrait s'avérer pratique pour cette fin. Elle utilise le fait que le monoxyde de carbone généré par l'oxydation du charbon peut être mesurée en analysant des échantillons de gaz émanant d'endroits spécifiques dans une pile, et que la localisation des points chauds peut alors être déduite de la forme des surfaces de concentration en CO que l'on peut construir à partir de telles données.

Ce concept a été testé en laboratoire au moyen d'une chambre de réaction cubique dans laquelle le gaz pouvait être injecté par une série de ports et des échantillons de gaz prélevés a partir de tubes de suivi poreux traversant le réacteur. Les expériences ont été centrées sur des simulations d'oxydation du charbon ainsi que sur une oxydation du charbon soutenue à l'O_2 à des températures elevées.

Pour les expériences de simulation, le réacteur était rempli de 'pois' de polystyrène; un point chaud était créé par injection de CO à proximite du fond de réacteur; et un courant d'air chaud traversant l'empilement, qui aurait pour résultat d'étaler le CO, était simulé en introduisant un courant

lent d'azote à proximité du port d'injection du CO. Des échantillons de gaz pour analyse étaient prélevés à partir de trois emplacements dans chaque tube de suivi, et la mesure des concentrations en CO a été utilisée pour construire des surfaces de concentration en CO à divers niveaux dans le réacteur.

Pour les éssais d'oxydation du charbon, le réacteur était rempli sans tassement de charbon broyé (mesh +28); un petit radiateur électrique était inséré immédiatement sous l'elément de charbon où un 'point chaud' devait être créé; la température du charbon était élevée à environ 220°C; et suffisamment d'oxygène était injecté près de la base du point chaud en cours de développement pour entretenir l'oxydation du charbon. Comme précédemment, des échantillons de gaz etaient preleves a partir de tubes de suivis localises en divers endroits, et les données d'analyse ont été utilisées pour la construction de surfaces de concentration en CO.

Dans tout les cas, sauf lorsqu'effectivement exclu en raison de l'échelle de l'expérience, ces surfaces localisaient le point chaud avec une bonne précision. Les exceptions étaient des cas où les 'zones d'influence' de deux point chauds se recouvraient, ou lorsque les courants de CO provenant de points chauds situés sur des cotés opposés du réacteur 'entraient en collision'. Un test examinant la possibilité d'utiliser du CO_2 - généré concurremment au CO par l'oxydation du charbon - comme alternative pour le suive des points chauds a fourni des données excluant une situation précise des points chauds et n'a donc pas été poursuivie plus longtemps.

Les informations dérivant de cette étude rendent valable la poursuite le

l'expérimentation sur en empilement de charbon plus grand afin de développer plus avant la procédure.

1. INTRODUCTION

When exposed to the atmosphere, freshly mined coal 'weathers' and will consequently deteriorate. Dehydration will impair its mechanical integrity; concurrent oxidation will progressively devalue almost every other property that lends it a particular technical value as a fuel or feedstock; and if it is a low rank coal - i.e., a lignite or a subbituminous coal - such deterioration will be compounded by a tendency to 'spontaneously' heat and ignite.

This phenomenon, commonly referred to as 'spontaneous combustion' but more properly termed autogenous heating, is due to oxidation of carbon to CO_2 - a reaction that ultimately releases c.395 kJ/mole - and to the fact that the rate of this reaction very nearly doubles with every $10^{o}C$ rise in temperature. Unless the reaction heat is effectively dissipated, the oxidation process will therefore accelerate exponentially, and the heats generated by it will likewise exponentially increase.

Because autogenous heating poses serious hazards when low rank coals are stored in the open or transported over long distances, such coals are generally only used in mine-mouth applications; and where storage cannot be avoided, construction of stockpiles follows empirical 'rules' which experience over many decades has shown to minimize heating hazards. It is thus common practice to put the coal down in 25-30 cm thick layers and to compact each layer before depositing the next; to limit slope angles to less than 15^{o} in order to prevent size segregation; and to 'crown' the pile

slightly to facilitate water run-off and minimize windrowing.

As well, stockpile maintenance procedures reflect an appreciation of how autogenous heating is initiated. At ambient atmospheric temperatures, oxidation of carbon proceeds too slowly and/or under conditions that preclude significant heat accumulation, and autogenous heating will therefore only pose problems if or when temperatures are boosted to levels at which the reaction rate can begin to accelerate. But that will happen if moisture in the coal is allowed to fall below the 'air-dried' moisture content of the coal[1] and the coal is then wetted [1].

Early field reports [2-4] speak of 'spontaneous combustion' in open stockpiles occurring most often (i) after rain following upon a period of warm, dry weather, (ii) when dry coal is dumped onto wet ground, or (iii) when wet coal (e.g., from a cleaning plant) is unloaded onto dry coal[2]; and later laboratory studies [1, 5-9], in which water-saturated nitrogen was passed through partly dry coal, showed that such wetting could raise temperatures by up to 30°C - and so cause an eight-fold increase of oxidation rates[3].

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1. As a rule of thumb, this runs to some 60-65% of the 'bed' or 'capacity' moisture content.

2. In the latter instances, heating was always found to begin at the interfaces between wet and dry coal.

3. Oxidation of pyrite to iron sulphates, a process that generates c.840 kJ/mole and involves a pyrophoric intermediate [10], is at best a secondary factor: low rank coals that are almost entirely devoid of pyrite are no less susceptible to autogenous heating by virtue of that fact.

Parenthetically it is worth observing that this mechanism explains why only low rank coals - i.e. porous, open-structured coals that present large internal surface areas to wetting and oxidation - are liable to heat autogenously. But whether a hot spot created by wetting remains 'alive', and can then launch accelerating oxidation, or is effectively killed depends on the minutiae of air flow in the pile and is at present quite unpredictable. Autogenous heating must consequently be viewed as involving randomly meandering hot spots in the coal; and since that makes it virtually impossible to anticipate potentially dangerous heating by monitoring a coal pile with thermocouples - and difficult to detect it after a hot region has formed - it becomes pertinent to explore other, possibly more reliable monitors.

Extant mathematical models that purport to describe autogenous heating [11-14] offer little assistance here. For the sake of simplicity, these all assume absence of radial heat and mass transfer, and limit themselves to one-dimensional treatments that represent 'essential' parameters by a set of three or four differential equations or, in one instance [12], by two coupled partial differential equations. In a few cases, these models seem to predict some facets of coal behaviour reasonably well. Distributions of free oxygen in a stockpile were found [15] to stand in good accord with inferences from Norden's model [11]; and one important aspect of Quan's model [11] has been tentatively confirmed by Stott et al. [16,17]. But as they stand, the models can neither predict where hot spots are likely to develop nor help locate them once they have been generated in a pile. Progress on these points could conceivably accrue from recourse to a stochastic probability model, but no

such model is currently at hand, and developing one may prove difficult [18].

There may, however, be some direct means for locating hot spots before they become dangerous.

One such possibility presents itself in the fact that coal oxidation at relatively low temperatures generates carbon monoxide, and that concentrations of this gas - more reliably measurable than temperatures which necessarily depend on the distance between a hot spot and the hot junction of the nearest thermocouple - could yield concentration profiles from which hot spot locations might be inferred.

The results of this study (see Secs. 3 and 4) support that view, but also reveal some factors that tend to preclude a definitive investigation of this procedure in the laboratory.

2. EXPERIMENTAL DESIGN AND EQUIPMENT

The theoretical basis of the experimental work lies in a simple two-dimensional model in which two perforated tubes traverse a pile of broken coal (see FIGURE 1). Air flow through the coal would make any CO generated at X move upwards; and in a more 'real' three-dimensional case, gas samples taken at appropriate locations within the tubes could therefore yield concentration surfaces that indicated the seat of the CO emission by their shapes. The two broken lines in Figure 1 - equivalent to surfaces in a three-dimensional model - illustrate how hot spots would be pinpointed.)

The reactor vessel in which this concept was experimentally tested (see FIGURES 2 and 3) was a 45 cm stainless steel cube fitted on two opposite sides with matched sets of ports through which porous monitor tubes could be inserted and nitrogen and/or other gases injected. The 50 cm long, 6 mm i.d. monitor tubes were fabricated from coarsely sintered granulated brass, possessed 2 um pores that allowed free in-and-out diffusion of gases and were, like all unused ports, closed by rubber nipples through which gas samples could be taken for analysis.

Gas samples could be withdrawn from any pre-selected point within the tubes, but were for the purposes of this study always taken at three sites, respectively 7.6, 23 and 38 cms in from the entry port. To minimize disturbance of gas concentration gradients along the monitor tubes, all samples were collected through appropriately long, prepositioned 0.5 mm i.d. stainless steel tubes that were externally connected to gas syringes.

Gas analyses centered on CO as well as, in later runs, on CO_2 and used gas chromatographic techniques that could detect these gases at concentrations as low as 10 ppm. But because very small volumes of CO and CO_2 can accrue by desorption from fresh coal rather than from oxidation per se, and were in fact likely to do so, only concentrations greater than 0.05% were recorded.

To generate CO, a temperature-controlled 4 cm^2 electric heater, cut from commercially available heating tape, was inserted just below the coal from which the gas was to form. This allowed temperatures to rise to as high as 250°C and sufficed to create sustainable 'hot spots'.

The coals selected for this study were a lignite and four subbituminous coals. TABLE 1 shows their ASTM rank designations as well as their geological and geographic origins.

3. THE 1st TEST SERIES

In order to simplify some preliminary test runs, conditions in an exposed coal pile during autogenous heating were simulated by loosely packing the reactor with polystyrene bubbles; injecting pure carbon monoxide at 20 ml/min through a port at {x=2; y=1}, and introducing nitrogen at 100 ml/min through ports at {x=1,4; y=1} in order to drive the CO upwards. (The port locations and placement of the monitor tubes are shown in FIGURE 3.) Analyses of gas samples withdrawn during runs carried out in this manner showed that CO concentrations fell quite consistently from about 4.3% at 7.5 cm from {x=2; y=2} to less than 1% at corresponding positions in the other three monitor tubes as CO spread throughout the reactor.

Since this clearly supported the view that 'hot spot' detection via measurement of CO concentrations was feasible in principle, further tests sought to define CO concentration surfaces. Technically, these experiments replicated the earlier experiments. However, gas injection ports varied between different runs; care was taken to establish steady state conditions in the reactor before any gas was sampled; and samples for analysis were now systematically collected at three points in each monitor tube. The sampling sites are shown, numbered, in FIGURE 4.

Typical results from routinely duplicated test runs are presented in FIGURES 5(a)-(e).

In Figures 5(a-c), the pronounced 'distortion' of the lower concentration surfaces point quite unequivocally toward the CO injection port, while the

flatter upper surfaces, although still influenced by the simulated hot spot at {x=2; y=1}, {x=1; y=1} or {x=5; y=1} respectively, clearly reflect gas spreading. In Figures 5(d) and (e), this situation is reversed because the simulated hot spot is now located at {x=1; y=3}. (The slightly different CO concentrations reflected in the shapes of the upper surfaces in the two diagrams are due to injection of nitrogen at different ports.)

As follow-up on the runs illustrated in Figures 5(a)-(e), three additional sets of experiments were carried out under simulated pile conditions. These were designed to define concentration surfaces in the x-z and y-z planes, and for that purpose used the monitor tube arrangements shown in FIGURES 6(a) and (b). Each set therefore required two runs under identical conditions. As in some previous experiments (s. above), CO was introduced at 20 ml/min through the {x=2: y=1} port; nitrogen was injected at 100 ml/min through {x=1;y=1}; and gas samples for analysis were withdrawn from the monitor tubes at the twelve locations shown in FIGURE 4.

All three sets of this series furnished almost identical data (see FIGURE 7). The concentration surface in the x-z plane always featured the same sharp upturn directly above the CO inlet port at {x=2;y=1} as was recorded earlier (see Figures 5a-e), and the y-z surface was characterized by a slight 'bulge' that reflected N_2-driven CO moving toward the upper right rear region of the reactor and showed CO concentrations falling from front to rear.

4. THE 2nd TEST SERIES

With simulation experiments consistently substantiating expectations from the 'model' referred to in Sec. 2, the study proceeded to test runs with coal.

For this work, the reactor was filled with coarsely crushed +28 mesh coal[4] on a 3 cm base of polystyrene 'peanuts'; provisions for creating a hot spot were made by electrically heating an approximately 4 cm^2 coal element; and an coal oxidation was initiated and sustained by injecting oxygen or air that also served to drive oxidatively generated CO upward to the gas sampling sites.

Test runs in which air was introduced at 60 ml/min through a port immediately below the heated coal, and coal temperatures were successively raised to 50^o, 60^o, 80^o and 100^oC failed to generate detectable concentrations of carbon monoxide; and runs in which (i) air at 30 ml/min or (ii) oxygen at 40 ml/min was used in attempts to initiate sustained oxidation at $80-100^oC$ proved equally unsuccessful[5].

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4. For most experiments, a subbituminous B coal from Pit #3 of TransAlta Utilities' Sundance Mine at Wabamun, 75 km west of Edmonton, was used. A freshly mined bulk sample of this coal was stored in sealed 18-litre drums under nitrogen until actually required for the tests.

5. Runs with reduced air flow were predicated on the supposition that flow at 60 ml/min effectively cooled a developing hot spot and thereby made for appreciably lower coal temperatures than indicated by the thermocouple. The use of oxygen instead of air was prompted by a possibility that better success might be achieved with higher O_2 partial pressures.

Sustainable hot spots could, however, be created at temperatures near 220°C when oxygen was injected at 100 ml/min, and these were accordingly set as base conditions for all experiments with coal.

In one series of experiments, the coal was brought to 220+/-5°C immediately above {x=1, y=1}; oxidation to CO was sustained by injecting O_2 at 100 ml/min through the {x=1; y=1} port; and after steady state conditions had been reached, gas samples were withdrawn from the twelve locations identified in Figure 4. FIGURE 8 presents the results in a vertically expanded form. The shape of the x-z concentration surface over y=2 identifies the hot spot site quite unequivocally but, as would be expected, slopes down as one moves away from {x=2; y=2}; and while the x-z concentration surface over y=3 is still slightly distorted by CO from the hot spot, it as well as the the surface over y=4 clearly show the effect of increasing distances from the hot spot.

But there are circumstances that make observed CO concentrations depend upon the particular <u>configuration</u> and/or limited <u>scale</u> of a laboratory experiment - and that thereby preclude correct location of hot spots from bench-scale data.

One example of such circumstances showed up in an experiment which - since low temperature oxidation generates CO_2 as well as CO - sought to explore the use of that gas as an alternative to CO for early detection of autogenous heating. Previous experiments of this test series were therefore repeated - i.e., the coal was brought to 220+/-5°C and oxidation was supported by injecting 100 ml O_2 per min through the {x=1; y=1} port - but gas samples taken in the monitor tubes were now analyzed for CO_2 as well as CO.

Concentrations of CO agreed well with previously measured values (see Figure 8); but as illustrated in FIGURE 9, CO_2 x-z concentration surfaces over y=2, y=3 and y=4 were characterized by 'distortions' that were unrelated to the hot spot location near {x=1; y=1}. A possible explanation may lie in a combined effect - i.e. in (i) partial CO-oxidation by O_2 at 220°C and (ii) gas flow in the packed coal forcing relatively heavier CO_2 to move horizontally before allowing it to spread upward.

Another example of a situation in which a laboratory experiment fails to correctly site hot spots is provided by the case in which the 'areas of influence' of two hot spots - one much more intense than the other - tend to overlap. This is illustrated by an experiment in which

(a) one hot spot was generated by injecting 100 ml O_2/min at {x=1; y=1} and producing CO from coal held at 220+/-5°C immediately above that port; and

(b) a second, more intense hot spot was simulated by introducing CO at 20ml/min through {x=4; y=1) and spreading it upward by injecting nitrogen at 180 ml/min through {x=5; y=1}.

As shown in FIGURE 10, the distortion of the x-z concentration surface over y=2 then effectively ignores the first hot spot by pointing only to the second, and concentration surfaces over y=3 and y=4 seem to reflect little more than local variations in the packing density of the coal.

A similar situation, but here aggrevated by the fact that CO concentrations indicate neither of the two hot spots, is shown in FIGURE 11. In runs which yielded these data, two hot spots were simultaneously simulated by injecting

20 ml CO/min

(i) at the reactor front through the (x=1; y=1; z=1) port, and

(ii) at the reactor rear through the (x=5, y=1; z=6) port,

and CO was made to spread by introducing nitrogen at 20 ml/min through (x=3; y=1; z=1) as well as through (x=3; y=1; z=6).

Not unexpectedly, the x-z concentration surfaces over y=2, y=3 and y=4 show in this case broad, diffuse maxima at locations that correspond to half the length of the monitor tubes - presumably because the opposing gas streams tend to collide here.

4. COAL CHARACTERIZATION: FIRST APPEARANCE OF CO

In Sec. 1 (Introduction) it was noted that wetting of excessively dry coal can increase its temperature by as much as 30°C and therefore, depending on ambient air temperatures, bring coal to a point at which, failing effective countermeasures, a progressive heat up becomes virtually inevitable. With this in mind, it was thought pertinent to determine the temperatures at which low rank coals actually begin to generate CO at rates that might be detectable in a pile.

To obtain such information, each of the five, compositionally very similar coals listed in TABLE 1 were subjected to two tests.

In one, a representative c.20 g sample of pulverized (-100 mesh) coal was progressively pyrolyzed in a slow stream of nitrogen at c.5°C/min, and gas samples for g.c. analysis were collected at 2 min intervals.

In the second, a fresh sample of the coarsely crushed coal - prepared as for the experiments detailed in Sec. 3 - was inserted into the reactor immediately over the heating tape and slowly heated; O_2 was introduced through a port just below the coal; and gas samples analysis were withdrawn at two ports above the coal.

Although neither experiment was expected to furnish more than a close estimate of the temperatures at which CO begins to be generated in measurable amounts, the data shown in TABLE 2 are considered accurate to within better than +/-10°C.

5. CONCLUSIONS AND RECOMMENDATIONS

The generally good agreement between CO concentrations recorded, under substantially identical experimental conditions, at corresponding reactor locations validates the significance of the concentration surfaces presented in Figures 5-11, and allows the conclusion that these diagrams fully substantiate the concept which prompted this study.

As well, there is little doubt that circumstances which tend to interfere with correct location of a hot spot, and in some cases make it impossible to do so (see Sec. 3), can be ascribed to the limitations of scale and experimental design which usually beset a laboratory study.

There are, of course, uncertainties beyond those arising from the limitations of laboratory work. Laboratory data do not enable statements about the size of a hot spot that would generate sufficient volumes of CO for detection in a large coal stockpile. And from a practical standpoint equally important is whether an adequate number or arrangement of perforated pipes for gas sampling can be installed in such a pile without seriously impeding later retrieval of coal.

But the information now at hand certainly warrants active pursuit of CO monitoring as a potentially practical method for early detection of autogenous heating. It is therefore recommended that serious consideration be given to the construction of a suitably equipped open coal stockpile in

which the technique could be further developed. An appropriate size might be something between 50 and 100 tonnes, and an appropriate location would be the Coal Research Centre at Devon, Alberta, where adequate space could be dedicated and where the necessary staff, facilities and infrastructure would be available.

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18. This emerged from discussions with Dr. J. Berkowitz, President of Berkowitz & Associates, Statistical and Mathematical Consultants, Vancouver.

Table 1. The coals

	geol. origin & formation	geogr. location	ASTM rank
1.	L. Paleocene, Ravenscrag fm.	Estevan coal zone, Sask.	lignite A
2.	U. Cretaceous, L. Horseshoe Canyon fm.	Castor - Battle R., Alta.	subbit. C
3.	U. Cretaceous, L. Horseshoe Canyon fm.	S. Tofield Alta.	subbit. C
4.	U. Cretaceous / Paleocene, Scollard Member, Paskapoo fm.	Wabamun (Highvale mine) Alta.	subbit. B
5.	U. Cretaceous, L. Horseshoe Canyon fm.	Sheerness (Vesta mine) Alta.	subbit. C

Table 2.
Temperatures of first CO appearance

coal		T_1 *	T_2 **
1. lignite A	(Sask.)	160°C	200°C
2. subbit. C	(Alta.)	160°C	200°C
3. subbit. C	(Alta.)	160°C	200°C
4. subbit. B	(Alta.)	180°C	210°C
5. subbit. C	(Alta.)	160°C	200°C

* Detectable flow of CO begins in pyrolysis tests

** Apparent minimum temperature for sustained CO generation in 'hot spots' within loosely packed coal

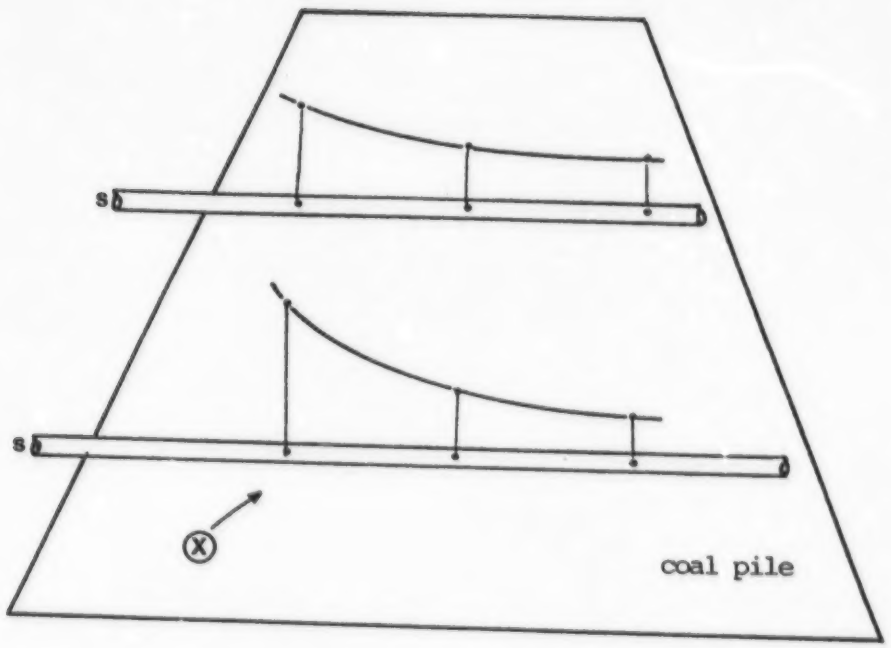

Figure 1.

The conceptual two-dimensional 'model'

Vertical distances between gas sampling sites (in sampling tubes s) and corresponding points on the curves indicate relative concentrations of CO moving upward from the 'hot spot' at X.

A mirror image of the lower curve would show maximum CO concentration pointing directly toward X.

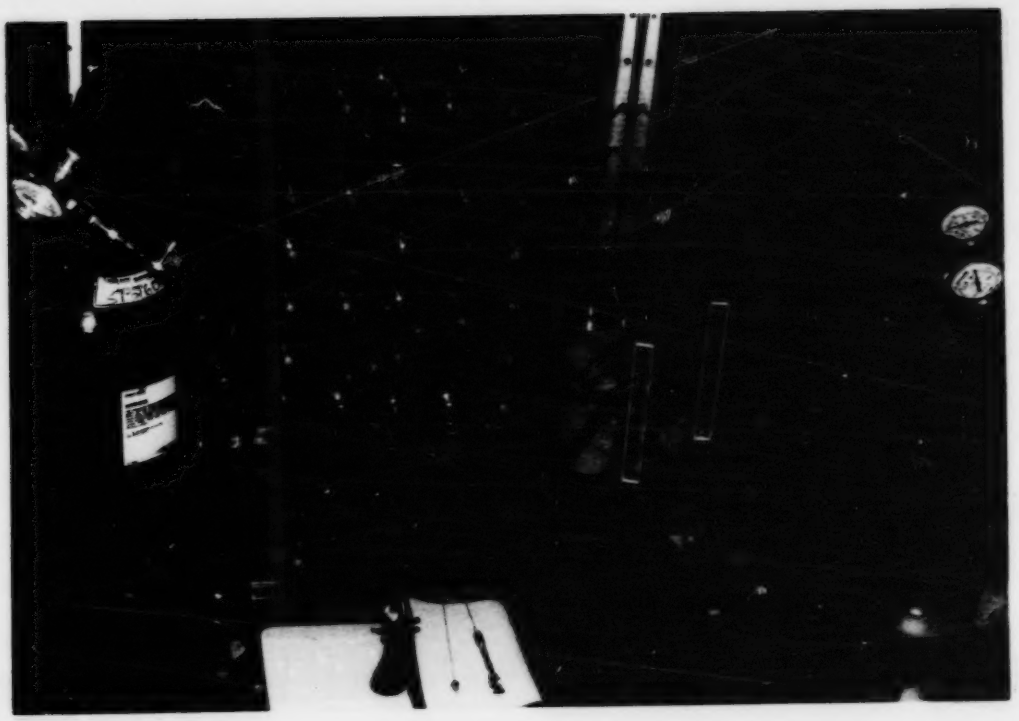

Figure 2. View of reactor assembly, showing injection ports and inlet ends of four monitor tubes.

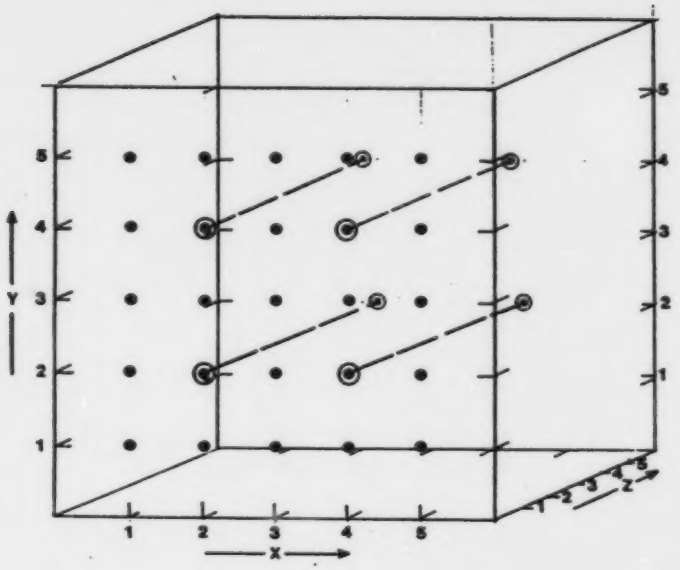

Figure 3.

Reactor schematic showing numbering system for identifying ports. Four monitoring tubes are located with inlets at, respectively,

[x = 2; y = 2]

[x = 2; y = 4]

[x = 4; y = 2]

[x = 4; y = 4]

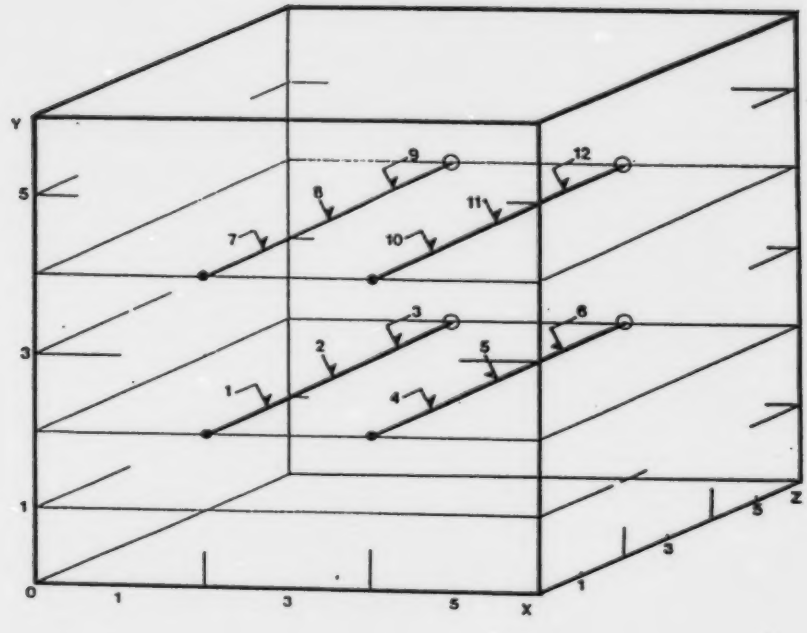

Figure 4

Gas sampling sites in monitor tubes.
The schematic shows four monitors.

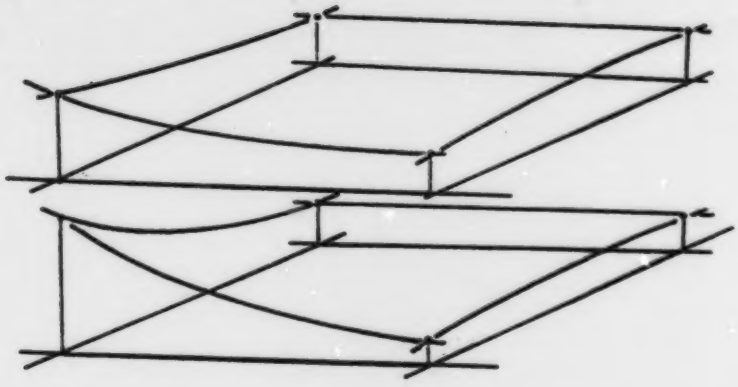

Figure 5(a)
N_2 in at (x = 1, 4; y = 1)
CO in at (x = 2; y = 1)

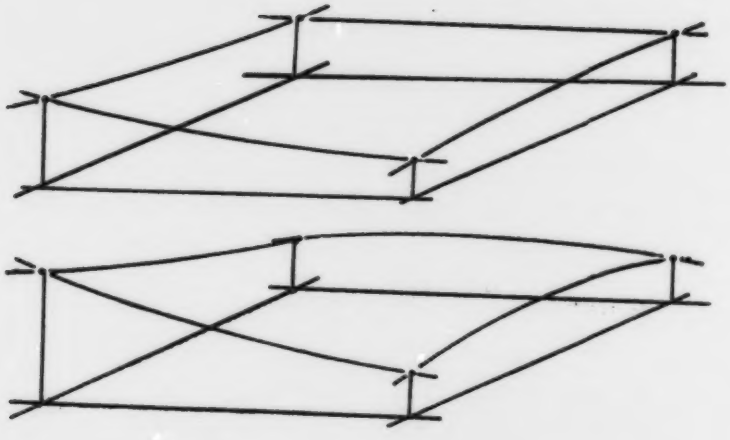

Figure 5(b)
N_2 in at (x = 3, 5; y = 1)
CO in at (x = 1; y = 1)

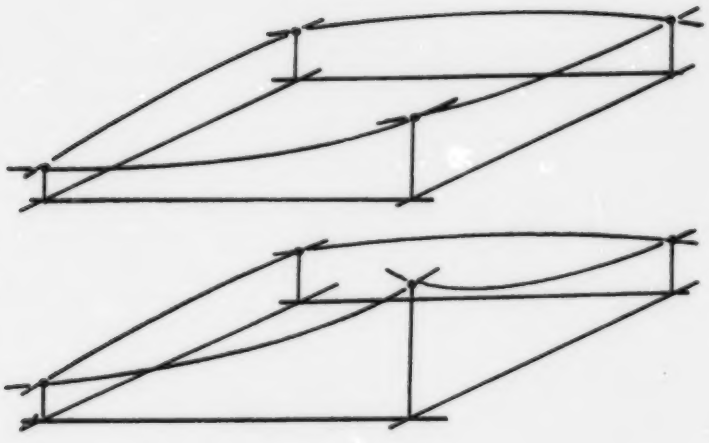

Figure 5(c)

N_2 in at (x = 1,3; y = 1)

CO in at (x = 5; y = 1)

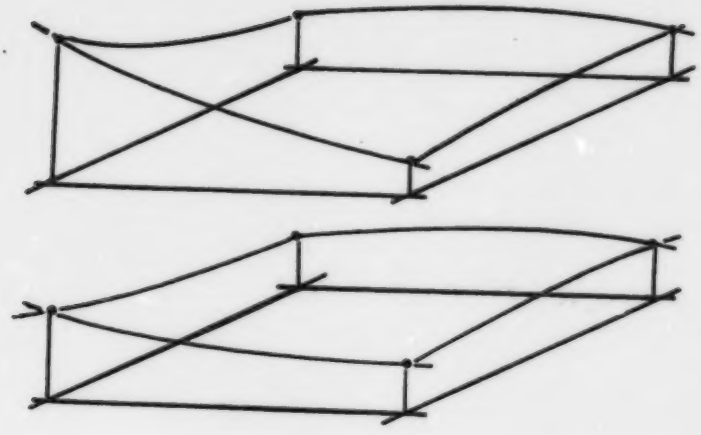

Figure 5(d)
N_2 in at (x=3, 5; y=1)
CO in at (x=1; y=3)

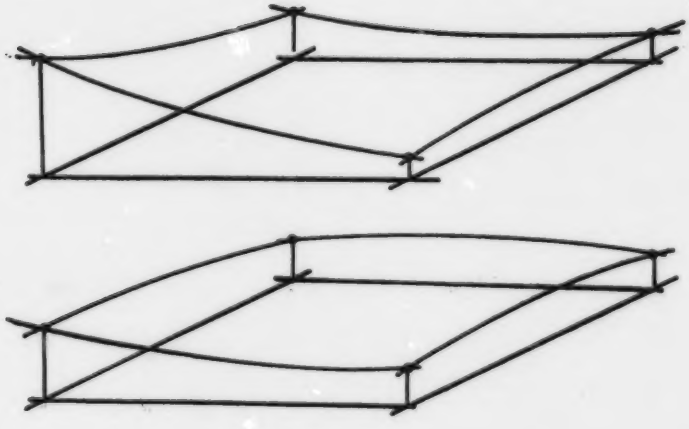

Figure 5(e)
N_2 in at (x=1, 5; y=1)
CO in at (x=1; y=3)

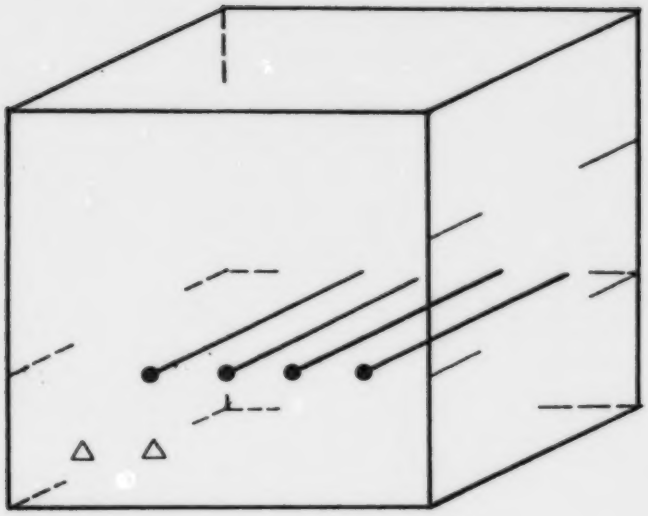

Figure 6(a)

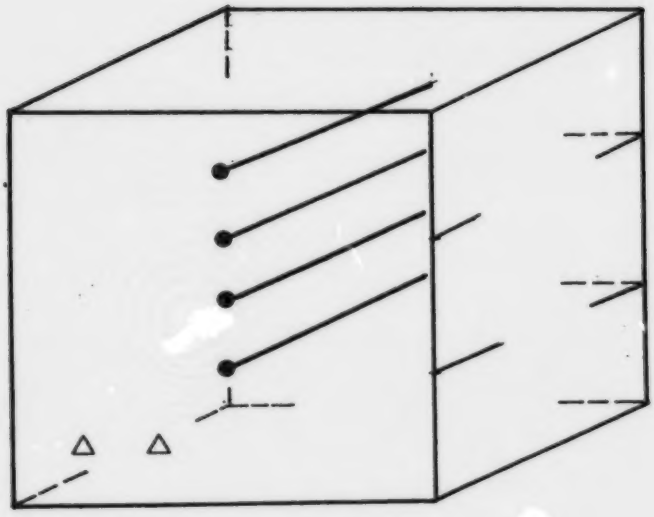

Figure 6(b)

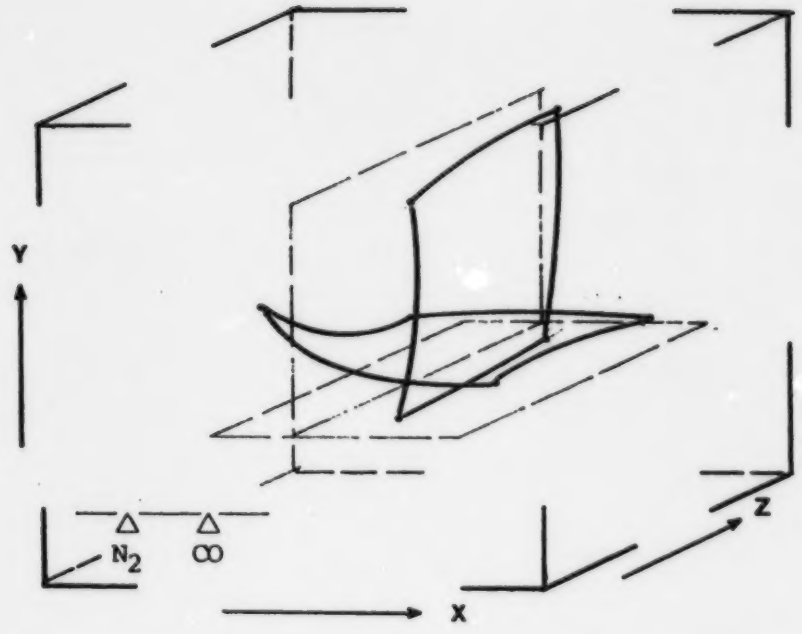

Figure 7

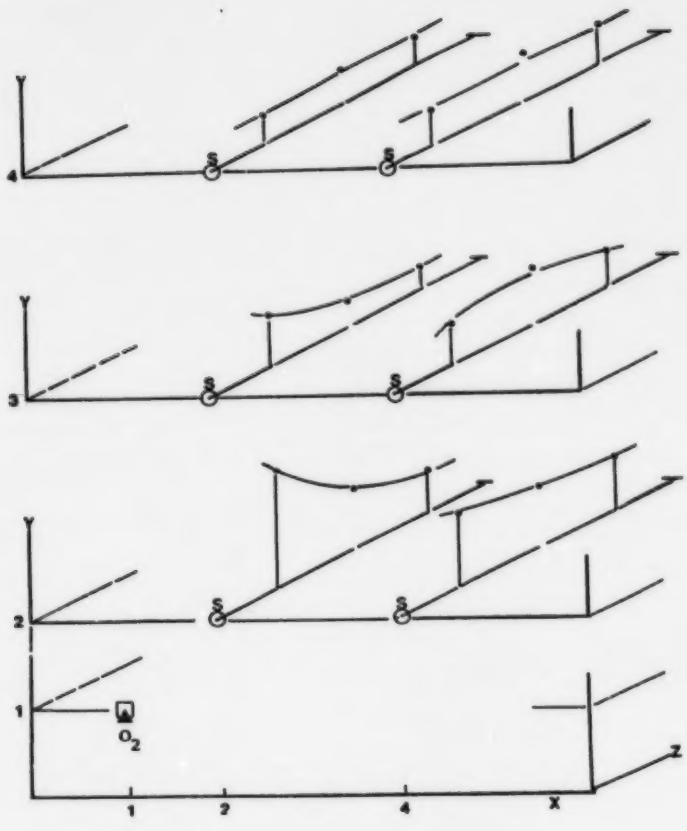

Figure 8.

s shows the placement of gas monitoring tubes at x = 2 and 4, y = 2, 3 and 4.

vertical distances between x-y planes and the corresponding points on curves above them show the relative CO concentrations.

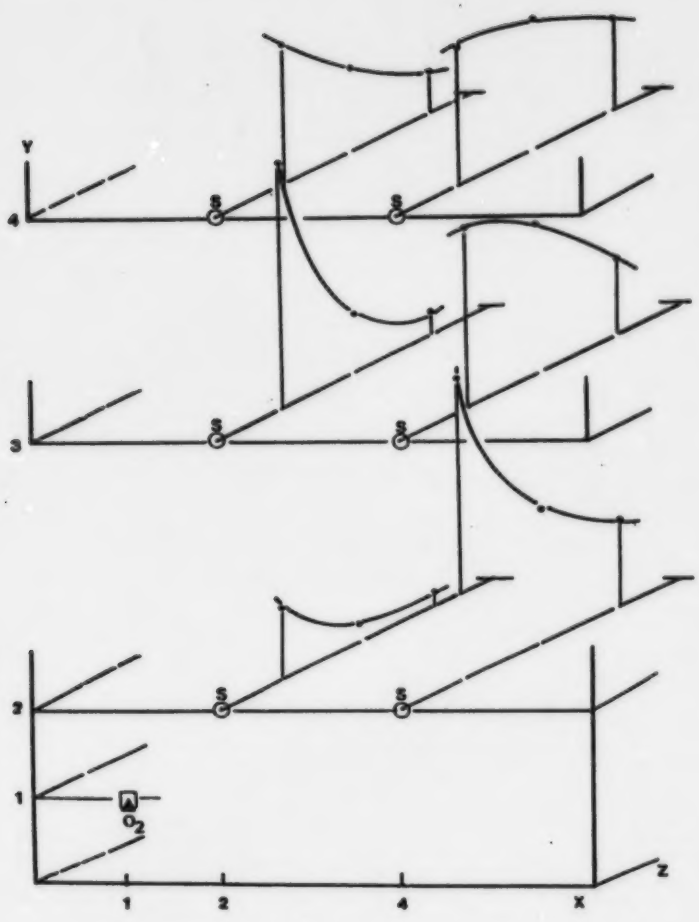

Figure 9.

s shows the placement of gas monitoring tubes at x = 2 and 4; y = 2, 3 and 4

vertical distances between x-y planes and the corresponding points on curves above them show the relative CO_2 concentrations.

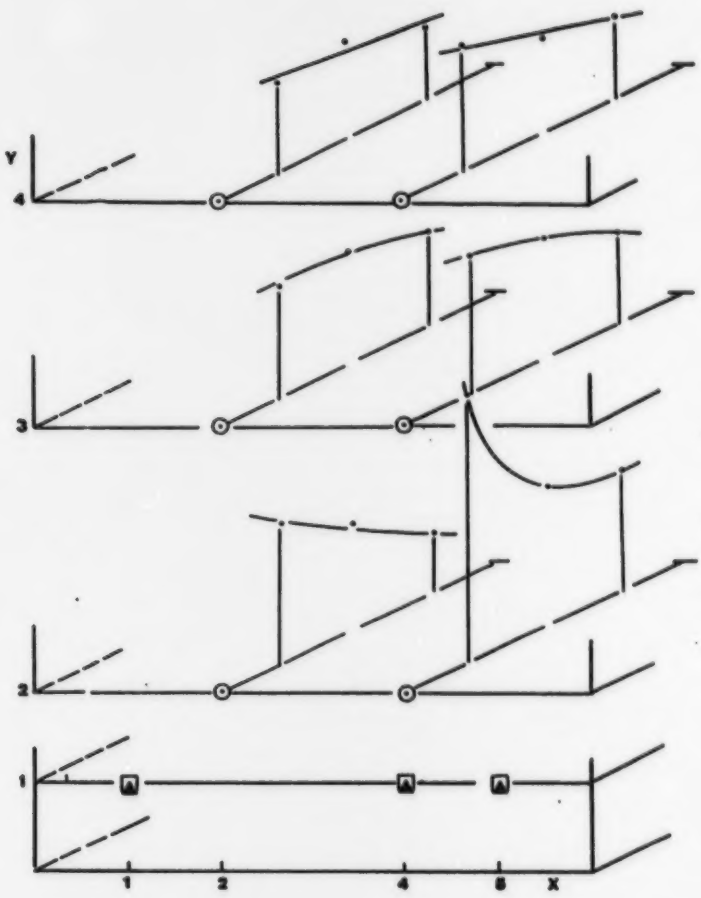

Figure 10.

O_2 in at [x=1; y=1]
CO in at [x=4; y=1]
N_2 in at [x=5; y=1]

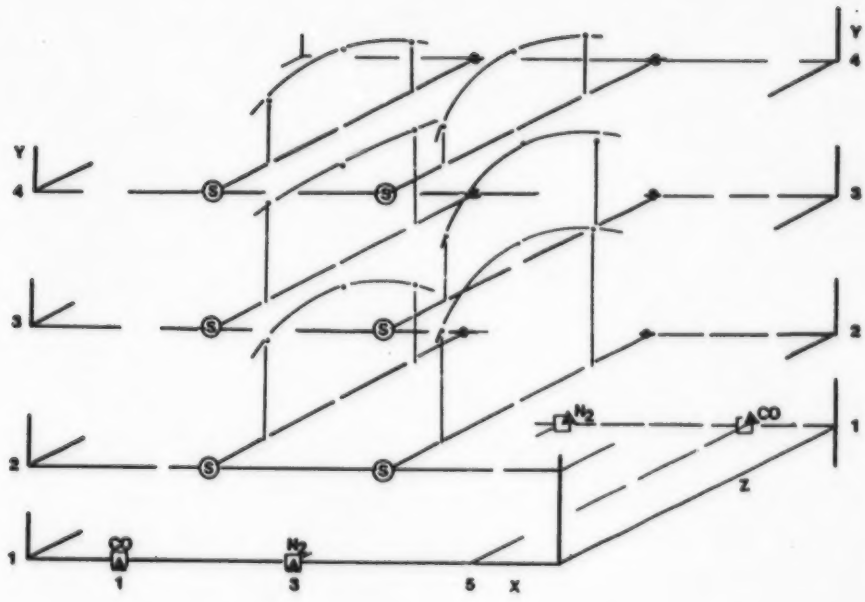

Figure 11 CO in at (i) [x = 1; y = 1; z = 0] (front)
(ii) [x = 5; y = 1; z = 6] (rear)

N_2 in at (i) [x = 3; y = 1; z = 0] (front)
(ii) [x = 3; z = 1; z = 6] (rear)